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Original Article

ESTIMATION OF DAMPING DERIVATIVES FOR DELTA WINGS IN HYPERSONIC FLOW FOR STRAIGHT LEADING EDGE

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ABSTRACT

Accurate estimation of the aerodynamic stability derivatives of airplanes is essential to evaluate the performance of the aircraft, whether civilian or military. Theoretical prediction methods for the dynamic stability derivatives at high angles of attack have not advanced, and in the present paper, an attempt has been made to study the effect of damping derivatives for delta wings for different angles of incidence, and the Mach number for a wing whose leading edge is straight. In this paper, the flow is considered to be unsteady flow and also considering the effect of the Leeward surface along with the shock waves and the expansion waves. The theory developed in the present paper considering the unsteady effects, the results have been estimated for speed flows for air assuming the air to behave as perfect gas for a range of angle of incidence and the inertia level. The results show that for Mach number M = 7 and above the damping derivatives becomes independent of inertia level. Increase in the damping derivatives is substantial when the angle δ is increased from 5 to 10 degrees.

KEYWORDS: Damping Derivative, Straight Leading Edge, Delta wing & Hypersonic

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1. INTRODUCTION

Computation of stability derivatives or dynamic stability derivatives has often been considered as critical parameters to predict the trajectory of the aircraft, missiles, rockets, aircraft bombs, and its dynamic stability and control results. Given the increased interest in supersonic/hypersonic flow, it is crucial to able to estimate the aerodynamic stability parameters in pitch, roll, and yaw for the wings, wedges, and cones as the individual identity as well as the complete unit when assembled with the aircraft. With the growth in wind tunnel facilities, availability of the enormous computational power due to the vast development in a fast processor has led the researcher to simulate the flow field instead go the wind tunnel tests straight away, due to the cost involved. Despite all these developments, analytical methods to estimate the stability derivatives still is a convenient and essential tool to estimate the aerodynamic derivatives initially and have an idea to optimize the design of the aerospace vehicles and hence reduce the cost involved in experimental tests. Given the above, the present analytical methods are handy to optimize the design before the models are fabricated for the wind tunnel tests.

With the increased usage of neutrally stable aircraft and sophisticated airframes, there is increasing demand within the aerospace community to improve the accuracy in its estimate and understanding of the aerospace vehicles.

Ghosh [3]–[6] has developed a 2-D hypersonic similitude which is valid for the large angle of incidence and developed the associated piston theory; it includes Light hill[1] & Milne's [2] piston theories. Ghosh has extended the large deflection similitude to non-slender cones, quasi cones, and also for wings provided the shock

waves are attached with the leading edge of wedge/cone/delta wings.

While developing the theory, we started with a three-dimensional, in hypersonic flow, the variations in the z-direction are negligible, and the three-dimensional problem is reduced to two-dimensional. When we consider the various strips at different locations along the span of the wing, it becomes independent of the strips. Hence, with these two assumptions, the three-dimensional flow is reduced to a one-dimensional flow or piston motions. Here, results are obtained from the second-order shock-expansion theory by getting the piston theory.

The overall stability of the wedge/wing is assessed based on the moment derivatives due to the pitch rate as well as incident rate are evaluated. The Ghosh [8] hypersonic similitude along with the Crasta& Khan [11]-[18] theory is integrated with the strip theory to obtain the unsteady moment derivative for a wing with the straight leading edge. The present work is an attempt to derive the relations for the estimation of dynamic stability in pitch from the analytical solutions by solving the continuity equation, momentum, and energy equation considering the air as the working fluid. The solution is obtained by using Rankine-Hugnoit relations.

Crasta and Khan developed a theory to evaluate the stability derivatives in pitch, which does not cater to the unsteady effect as the theory developed by them are a quasi-steady one. CFD Simulation with Analytical and Theoretical Validation of Different Flow Parameters for the Wedge at Supersonic Mach Number along with the numerical investigation of flow field by Khan [19]-[20]. In this paper, the effect of damping derivative at different pivot angle of incidence & Mach number has been evaluated and discussed in the section to follow.

2. ANALYSIS

The pitching moment per unit span about the pivot $x = x_0$ due to the only lower surface is

$$\overline{M} = \int_0^L (x - kL)\overline{P}_p \, dx$$

$$-\frac{\partial \overline{M}}{\partial \dot{\theta}} = \int_0^L (x - kL)\frac{\partial \overline{P}_p}{\partial \dot{\theta}} dx$$

$$-\frac{\partial \overline{M}}{\partial \dot{\theta}} = \int_0^L (x - kL)\rho_2 a_2 u_\infty \left(\frac{c_2 x}{u_\infty} + \frac{c_3 L}{u_\infty}\right) dx$$

For the windward side, the equation is

$$-\frac{\partial M}{\partial \dot{\theta}} = \rho_2 a_2 L^3 \left[c_2\left(\frac{1}{3} - \frac{k}{2}\right) + c_3\left(\frac{1}{2} - k\right) \right]$$

On the expansion side of the flat plate, the flow turns through a Prandtl-Meyer expansion at the leading edge to become parallel to the upper surface. First Mach number M_θ downstream of the expansion is determined first. At zero angle of attack, flat plate oscillating in a stream of Mach number $M_{\theta,}$ it is assumed that pressure perturbation is the same. Due to this approach, the oscillation of the expansion fan due to the flat plate oscillation is not accounted.

It is worth noting that the upper surface is at a much lower pressure than the windward surface. Contribution to damping at large Mach numbers is negligible as compared to windward surface.

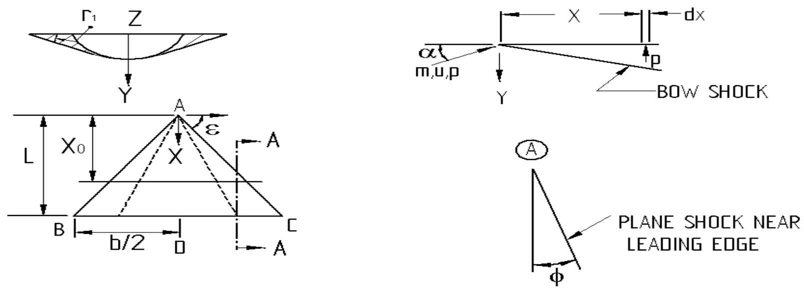

Figure 1: Different views of the Delta Wing.

$$V_p = \frac{u_\theta}{\cos\mu_\theta} + \frac{(x-kL)\dot{\theta}}{\cos\mu_\theta}$$

Piston Mach number

$$M_p = \frac{v_p}{a_\theta} = \frac{M_\theta \theta}{\cos\mu_\theta} + \frac{(x-kL)\dot{\theta}}{a_\theta \cos\mu_\theta}$$

$$\frac{\partial M_p}{\partial \dot{\theta}} = \frac{(x-kL)}{a_\theta \cos\mu_\theta} \quad (1)$$

M_θ is the Mach number downstream of the expansion fan, a_θ is the sonic velocity &μ_θ is the Mach angle downstream of Prandtl- Mayer expansion. The isentropic expression for pressure ratio is given by

$$\frac{p_p}{P_\theta} = (1 - \frac{\gamma-1}{2} M_p)^{\frac{2\gamma}{\gamma-1}}$$

As θ and $\dot{\theta}$ tend to zero, the equation for the acoustic expression

$$\frac{P_p}{P_\theta} = (1-\gamma M_P)$$

Pitching Moment,

$$\bar{M} = \int_0^L (x-kL)P_p dx = \int_0^L (x-kL)P_\theta(1-\gamma M_P)dx$$

$$-\frac{\partial \bar{M}}{\partial \dot{\theta}} = \int_0^L (x-kL)P_\theta(-\gamma)\frac{\partial M_p}{\partial \dot{\theta}}dx$$

From equation (1)

$$-\frac{\partial \bar{M}}{\partial \dot{\theta}} = -\int_0^L (x-kL)P_\theta(-\gamma)\frac{(x-kL)}{a_\theta \cos\mu_\theta}dx$$

$$-C_{m_{\dot{\theta}}} = \frac{4}{\rho_{\infty} u_{\infty} b L^3}\left[-\frac{\partial \bar{M}}{\partial \dot{\theta}}\right]$$

$$-C_{m_{\dot{\theta}}} = \frac{4\rho_2 a_2}{\rho_{\infty} u_{\infty}}\left[c_2\left(\frac{1}{8}-\frac{k}{6}\right)+C_4\left(\frac{k}{2}-\frac{k^2}{2}-\frac{1}{8}\right)\right]++\frac{p_{\theta}}{p_{\infty}}\frac{a_{\infty}}{a_{\theta}}\frac{M_{\theta}}{M_{\infty}}\frac{1}{\sqrt{M^2{}_{\theta}-1}}\left[\left(1-\frac{8k}{3}+2k^2\right)\cot\varepsilon\right]$$

3. RESULTS AND DISCUSSIONS

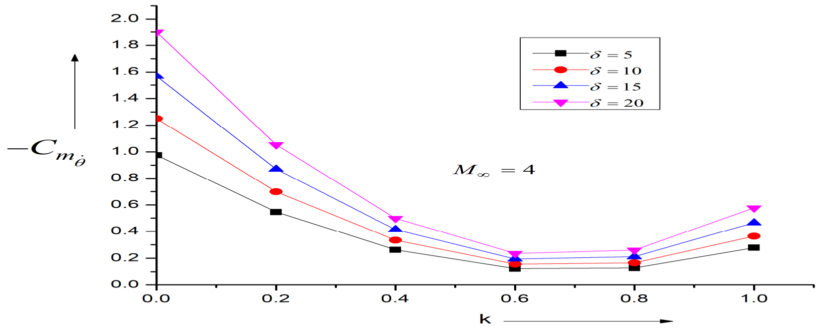

Figure 2: Variation of Damping Derivative with Pivot Position M_{∞} = 4.

“Figure 2 shows the variation of the damping derivative with a pivot position for the different angle of attack for a fixed Mach number M = 4. The results indicate that when the flow deflection angle is increased from five degrees to ten degrees. It is also seen that the percentage increase in the pitch damping stability derivatives for different pivot position is in the range twenty-eight to thirty percent. Similar results are seen when we look at the magnitude of the damping derivatives for flow deflection angles in the range from ten to fifteen degrees and fifteen degrees to twenty degrees. For the flow deflection band of ten to fifteen degrees, the variations in the damping derivatives are in the range twenty-five to twenty-seven percent. Whereas for the flow deflection angle increase in the range from fifteen degrees to twenty degrees, the damping derivatives remained in the range from twenty-one percent to twenty-four percent. From the results of figure 2, it is evident that the enhancement in the magnitude is considerable when the flow deflection angle is increased from five to ten degrees, and this trend is valid for the entire range of the pivot positions. With further increase in the flow deflection angle (δ) from ten to fifteen degrees and later from fifteen to twenty degrees this increase in the damping derivative is decreased all along for all the values of the pivot positions. The reasons for this trend may be the pressure distribution on the surface of the wing, the variations in the strength of the shock at this angle, and also the locations of the center of pressure for varied flow deflection angles”.

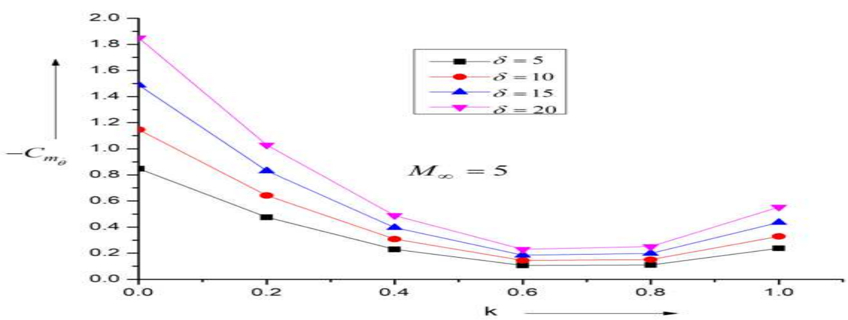

Figure 3: Variation of Damping Derivative with Pivot Position M_{∞} = 5.

"Figure 3 shows the variation of the damping derivative with a pivot position for the different angle of attack for a fixed Mach number M = 5. In the figure, it is seen that when the flow deflection angle is increased from to ten degrees, their sudden jump in the damping derivatives as compared to the values at Mach M = 4. Its value varies in the range from 35 % to 38 % for all the values of the pivot positions. When the angle of the flow deflection is increased from ten to fifteen degrees, there is a decrease in the magnitude of the stability derivatives due to the pitch, and the percentage increase in the values are in the range from 30 % to 33 % results. With further increase in the flow deflection angle of the wing results further, a decrease in the magnitude of the damping derivatives and values are in the range from 24 % to 27 % at various pivot locations. The results presented in the previous case were for Mach 4, which is the limiting Mach number, and the flow may be in transition. It is well known that the zone of supersonic/hypersonic Mach number will be dependent on unified supersonic/hypersonic similitude. The similitude is a function of Mach number and the flow deflection angle (δ). The angle δ may be one of the reasons for the sudden increase in the damping derivative of the wing when the Mach number is increased from M = 4 to 5. Even though the increment in the inertia level is just 25 %, however, the flow field has changed to a great deal. This may be the reason for this increase in the damping derivatives".

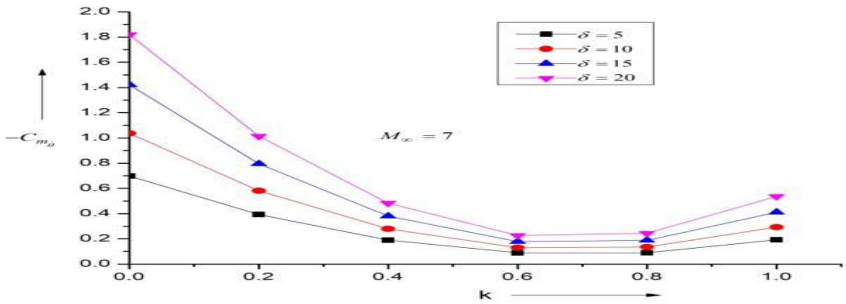

Figure 4: Variation of Damping Derivative with Pivot Position $M_\infty = 7$.

Figure 4 presents "the damping derivative values for Mach M = 7 for various flow deflection angles. When the Mach number is further increased from M = 5 to 7, results indicate that there is a further increase in the stability derivatives when the Mach number is increased from M = 5 to 7. This increase in the inertia level increases the damping derivatives. When the flow deflection angle is increased from 5 to 10 degrees, increases the damping derivative in the range 48 to 51 % for pivot positions 0 to 1. Similarly, with further increase in the deflection from 10 to 15 degrees and from 15 to degrees results in an increase from 37 to 40 percent and 28 to 31 percent. This increase in the magnitude of the damping derivatives is attributed to the increase in the inertial level and the plan form area of the wing".

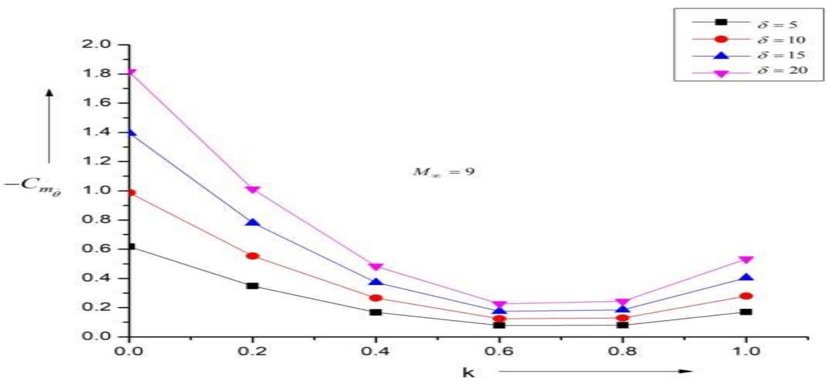

Figure 5: Variation of Damping derivative with Pivot position $M_\infty = 9$.

The damping derivatives for Mach number M = 9 are shown in Fig, 5 for various flow deflection angles. Here once again the increase in the surface area of the wing along with the increase in the Mach number results further increase in the magnitude of the damping derivatives in the range from 60% to 64%, 41% to 45%, and 30 % to 32% for flow deflection angle increase from 5 to 10 degrees, 10 to 15 degrees, and 15 to 20 degrees. It is seen that when the Mach number is increased, there is a substantial increase in the values of the damping derivatives

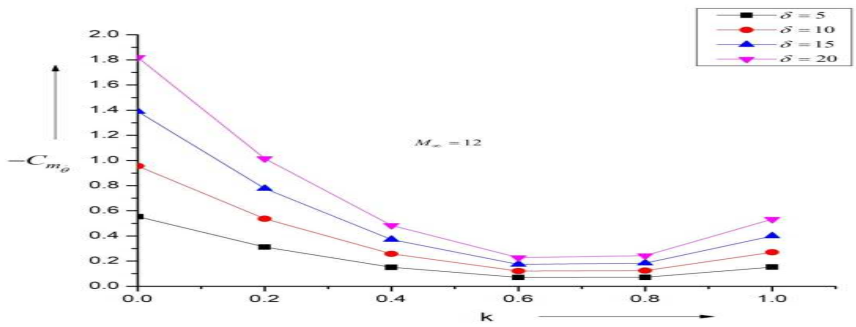

Figure 6: Variation of Damping Derivative with Pivot Position M_∞ = 12.

Results for Mach number M = 12 are shown in figure. 6. These results are on similar lines, as discussed earlier for lower Mach numbers. It is seen that with further increase in the Mach number has increased in the magnitude of the damping derivatives. Also, it is seen that there is a marginal increase in the damping derivatives due to the increase in the Mach number.

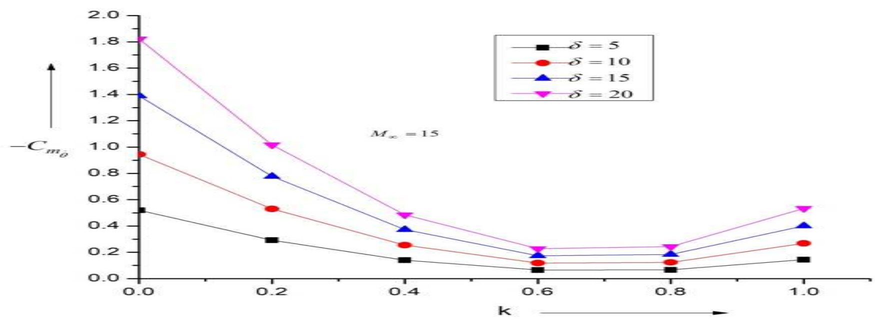

Figure 7: Variation of Damping Derivative with Pivot Position M_∞ = 15.

Figure. 7 shows results of damping derivatives for Mach M = 15. "While looking at the magnitude of the damping derivatives at various Mach numbers, the results indicate that the magnitude of the damping derivatives remained nearly constant from Mach M = 12 and above. These results reiterate that the aerodynamic stability derivatives become independent of Mach number for Mach number greater than 12. Nevertheless, there is a substantial increase in the damping derivatives when the flow deflection angle (δ) is increased from 5 to 20 degrees in steps of degrees. The increase in the damping derivatives is attributed to the increase in the wing plan-form area which results in an increase in the span of the wing and hence increases in the aspect ratio of the wing as the span of the wing will increase with the increase in the flow deflection angle δ. This increase in the damping derivatives for the increase in the (δ) from 5 to 10 degrees results in damping derivatives in the range from 82% to 86% for different pivot positions. When the flow deflection angle (δ) is increased from 10 to 15 degrees, it results in 47% to 49 % increase in the damping derivatives".

Similarly, for increase (δ) from 15 to 20 degrees results in 31 % to 33% in the damping derivatives. These results show that the maximum gain the stability derivatives is seen when the (δ) is increased from 5 to 10 degrees. For other

range of increase in (δ) result in a marginal increase in damping derivatives in comparison to the values when (δ) was enhanced from 5 to 10 degrees. The physics behind this trend may be the pressure distribution on the surface of the wing, the strength of the shock waves present at the leading edge of the wing and the location of the center of pressure.

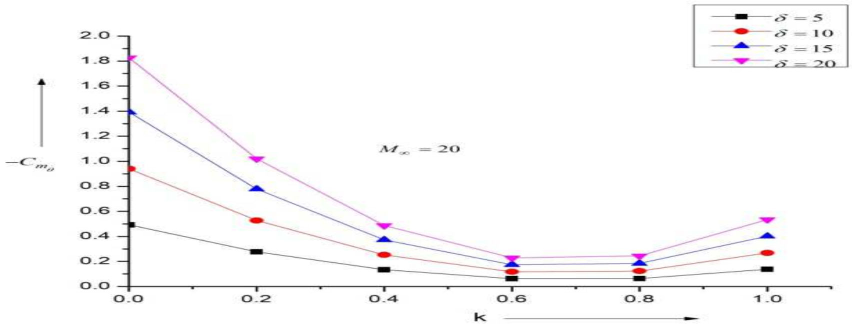

Figure 8: Variation of Damping Derivative with Pivot Position $M_\infty = 20$.

Results of damping derivatives for the highest value of the Mach number M = 20 of the present study is shown in figure. 8. From the results, "it is observed that due to the increment in the Mach number, there no change in the magnitude of the damping derivatives. However, due to the increase in the flow deflection angle from 5 to ten degrees which increases the plan-form area of the wing, finally results in a considerable increase in the damping derivatives and this values are ranging from 91% to 95 % for the pivot position variations from zero to one. When the angle δ is increased from ten to fifteen degrees, the increase in the damping derivatives lies in the range from 48% to 50%. Similarly, when the angle δ is increased from 15 to 20 degrees, it results in an increase of damping derivatives in the range from 31% to 33%. From these results it is evident that the increments in the magnitude of the damping derivatives are not linear, the increase is the maximum when the angle δ is increased from 5 to 10 degrees, and later with further, and increase in the angle δ leads to lower values of the damping derivatives". The reasons for this trend is due to the nature of the expression for the damping derivatives, which is not a linear equation; instead, it is a non-linear equation. Hence one cannot draw a definite trend; instead, one has to study on case to case basis.

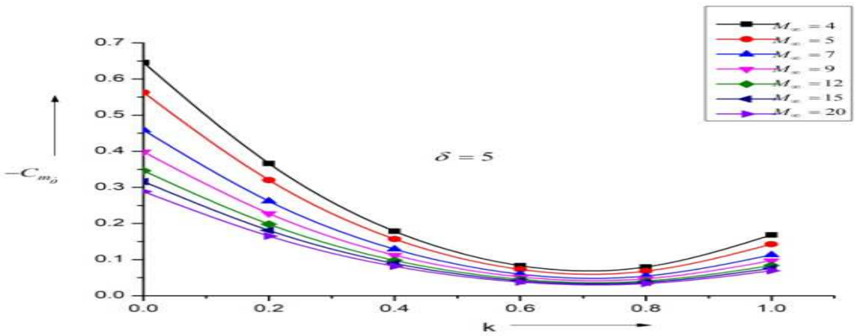

Figure 9: Variation of Damping Derivative with Pivot Position δ = 5.

Figure 9 shows the "damping derivative as a function of pivot position from 0 to 1 at different Mach number from 4 to 20 for a fixed value of the flow deflection angle $\delta = 5^0$. From these, it is evident that when the Mach number is increased from 4 to 10, there is a drastic change in the magnitude of the damping derivatives, as Mach number increases the damping derivative is decreasing. From the figure 9, it is observed that when the Mach number is increased from M = 4 to 5, results in 15 % to 18 % increase in the damping derivatives for a fixed value of δ = 5 degrees for pivot positions in the range o to 1. When the Mach number is increased from M = 5 to 7, results in a substantial increase in the damping

derivatives and its values are in the range from 23% to 26%. Similarly, when the Mach number is changed from M = 7 to 9 and as well as from M = 9 to 12, this increase in the Mach number results in a marginal increase in the damping derivative from 15% to 16% for both the ranges of the Mach numbers. But the trend of the variations in the damping derivatives for Mach number increase from M = 12 to 15 and M = 15 to 20, the stability derivative due to the rate of pitch does not change and remains steady state in view of the high values of the Mach number. It is well known that after a specific value of the Mach number, the trend will not change and will remain steady. Also, it is seen that the amount of decrement in the damping derivative is considerable for Mach number increase from 4 to 5 and 5 to 7. However, for other ranges of increase in the Mach number, the magnitude of the decrement of damping derivatives is progressively is decreasing with lower magnitude, indicating the attainment of Mach number independence principle".

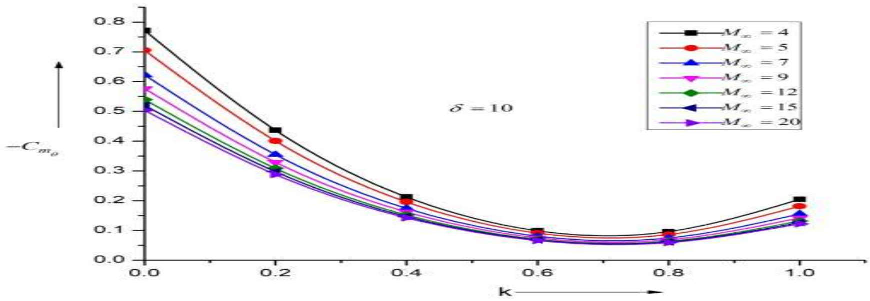

Figure 10: Variation of Damping Derivative with Pivot Position δ = 10.

Results of the damping derivatives for a fixed value of $\delta = 10^0$ for different Mach numbers are shown in Figure 10. As discussed earlier that "there is a significant increase in the magnitude of the damping derivative when the angle δ is increased from 5 to 10 degrees and later when the angle δ is increased either from 10 to 15 degrees or 15 to 20 degrees does not yield that much increase in the damping derivatives. Figure 10 indicates that when Mach number is increased from 4 to 5 results in 9 to 13 percent increase in the damping derivatives for pivot position 0 to 1. When Mach number is increased from 5 to 7 the increase in the damping derivatives is in the range from 13% to 17%". Similarly for Mach number range 7 to 9, 9 to 12, 12 to 15, and 15 to 20, the increase in the damping derivatives are in the range from 8 to 9 percent, 7 to 8 percent, 3.7 to 4.2 percent, and 3.3 to 3.7 percent for the pivot position of 0 to 1.

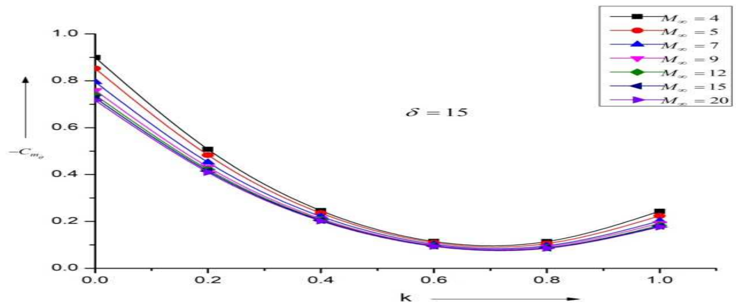

Figure 11: Variation of Damping Derivative with Pivot Position δ = 15.

Results of the damping derivatives for a fixed value of $\delta = 15^0$ for different Mach numbers are shown in figure 11. Figure 11 indicates that "when Mach number is increased from 4 to 5 results in 5.5 to 8.9 percent increase in the damping derivatives for pivot position 0 to 1. When Mach number is increased from 5 to 7, the increase in the damping derivatives is in the range from 7% to 11%. Similarly for Mach number range 7 to 9, 9 to 12, 12 to 15, and 15 to 20, the increase in the

damping derivatives are in the range from 4.6 to 4.8 percent, 2.8 to 5 percent, 1.7 to 2 percent, and 1.5 to 1.8 percent for the pivot position of 0 to 1. These results clearly demonstrate that for Mach number 7 and above for $\delta = 15^{0,}$ the stability derivatives have become independent of the Mach number".

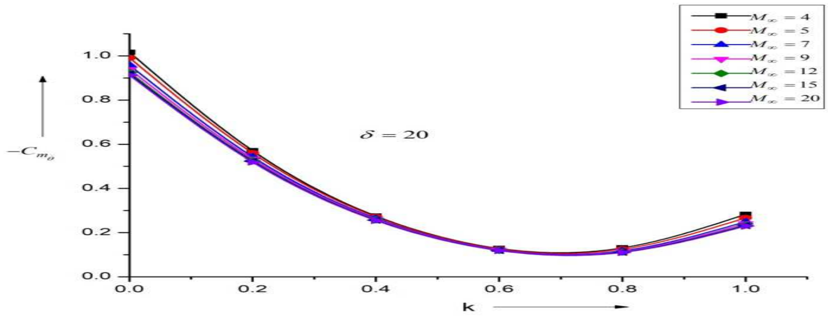

Figure 12: Variation of Damping Derivative with Pivot Position δ = 20.

Results of the damping derivatives for a fixed value of $\delta = 20^0$ for different Mach numbers are shown in figure 12. Figure 12 indicates that "when Mach number is increased from 4 to 5 results in 2.5 to 6 percent increase in the damping derivatives for pivot position 0 to 1. When the Mach number is increased from 5 to 7, the increase in the damping derivatives is in the range from 3.5% to 7%. Similarly for Mach number range 7 to 9, 9 to 12, 12 to 15, and 15 to 20, the increase in the damping derivatives are in the range from 2 to 3.5 percent, 1.5 to 2.6 percent, 0.8 to 1.3 percent, and 0.6 to 1.0 percent for the pivot position of 0 to 1. These results clearly demonstrate that for the Mach number 7 and above for $\delta = 20^0$ the stability derivatives have become independent of the Mach number as was seen in the previous figure when the flow deflection angle δ = 15 degrees. It is seen that the damping derivatives results for δ = 15 and 20 degrees are almost the same for the Mach number range from 4 to 20 with a marginal decrease in the magnitude of the damping derivatives for δ = 20 degrees".

4. CONCLUSIONS

"Based on the above discussions, we may draw the following conclusions:

- The damping derivative is very sensitive to the initial increase in the angle δ = 5 to 10 degrees. With further increase in the angle δ from 10 to 15 degrees or from 15 to 20 degrees, the increase in the magnitude of the damping derivatives is marginal. Larger the angle δ smaller the increase in the damping derivative, due to the pressure distribution on the surface of the wing, the variation in the span of the wing, and the shock wave structure at the leading edge.
- At the large Mach number M = 10 above the flow, the field becomes very complicated. With the increase in Mach number, shock wave angle continues to decrease, and after a specified Mach number, the shock wave angle β will become independent of the inertia level of the flow.
- With the increase in the Mach number, the strength of the oblique shock wave will increase, which will result in the shock wave and boundary layer interaction. Apart from this interaction, there will be a boundary layer and entropy layer interactions.
- For angle δ = 5 to 20 degrees, the Mach number independence principle is enforced, and the damping derivatives is independent of Mach number from M = 7 and above".

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